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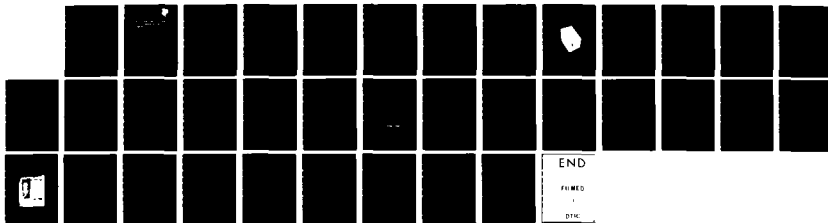
PHASE 2A BENCH MODEL DEVELOPMENT TACTICAL RUBIDIUM
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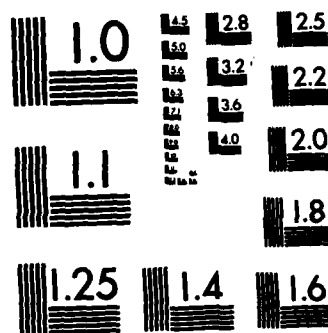
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Final Technical Report
December 1982



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PHASE 2A BENCH MODEL DEVELOPMENT, TACTICAL RUBIDIUM FREQUENCY STANDARD

EG&G Electronic Components

William J. Riley

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
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APPROVED:

Ferdinand Euler

FERDINAND K. EULER
Project Engineer

APPROVED:

Harold Roth

HAROLD ROTH
Director, Solid State Sciences Division

FOR THE COMMANDER:

John P. Huss

JOHN P. HUSS
Acting Chief, Plans Office

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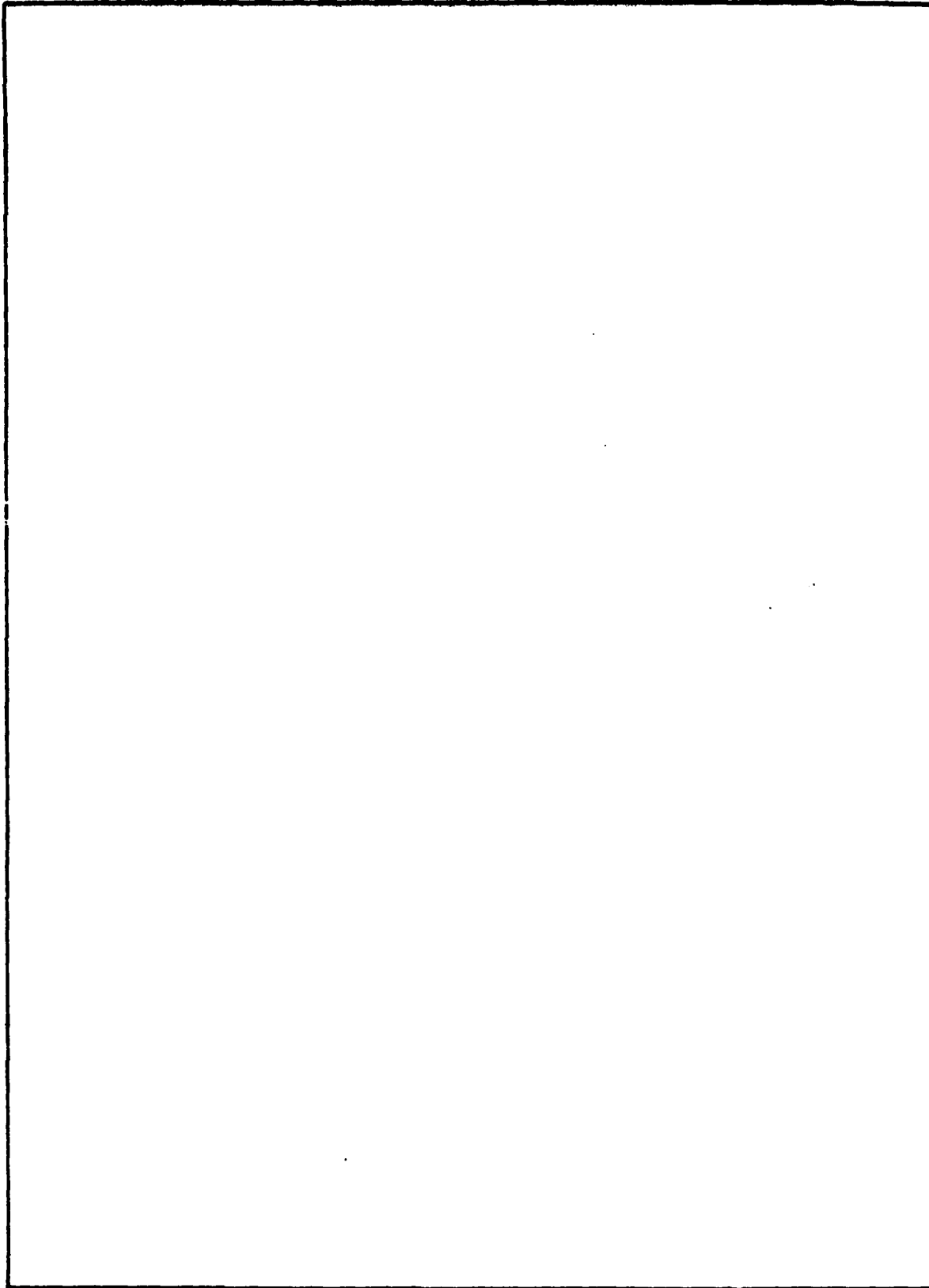
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TABLE OF CONTENTS

	<u>Page No.</u>
1.0 Introduction	1
2.0 Overall Design Progress	2
3.0 Block Diagram	4
4.0 Physics Package	6
5.0 Cell Processing	9
6.0 Servo Amplifier	10
7.0 VCXO Section	12
8.0 VHF Section	15
9.0 Power Section	17
10.0 Other Circuits	19
11.0 Bench Model Packaging	21
12.0 Summary of Results	23
13.0 Plans for Prototype Version	27

FIGURES

<u>No.</u>		
1	Photograph of TRFS Mockup Unit	3
2	TRFS Block Diagram	5
3	Layout of Miniaturized Physics Package	7
4	Servo Amplifier Schematic	11
5	VCXO Schematic	13
6	TRFS Phase Noise Plot	14
7	Schematic of Bench Model VHF Section	16
8	Schematic of Bench Model Power Section	18
9	Schematic of Bench Model Lamp Exciter	20
10	Photograph of TRFS Bench Model	22
11	TRFS Prototype Packaging Layout	28

TABLES

I	TRFS Physics Package Signal Parameters	8
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1.0 INTRODUCTION

This report summarizes the progress made during Phase 2A of an effort to develop a tactical rubidium frequency standard (TRFS) for the U.S. Air Force SEEK TALK program. The overall objective is to achieve a large scale production capability for an extremely small, rugged, and fast warmup atomic clock for avionics applications. This phase of the program accomplished the design, fabrication, and test of a working bench version of the TRFS.

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2.0 OVERALL DESIGN PROGRESS

The TRFS design approach was described in an EG&G technical proposal in June, 1981⁽¹⁾. It was based on a set of specifications chosen to meet the requirements of the two prime contractors working on the SEEK TALK program at that time. In general, the specifications represent a very small rubidium frequency standard of medium stability capable of rapid warmup and operation in a hostile environment. The design objective is to meet the most severe combination of current requirements for a device of this type.

The overall unit will consist of an ultraminiature rubidium physics package at the center of 4 plug-in circuit boards inside a 2½ inch square by 4 inch enclosure. A mockup of the complete TRFS is shown in Figure 1. The physics package, which is approximately the size and shape of a "D" flashlight battery, has now been further refined from its first version developed in-house by EG&G during Phase 1 of this project. Techniques have been worked out for the rubidium lamp and cell processing. The electronic development has progressed to the stage of successful evaluation of etched-circuit versions of most of the circuits. The mechanical packaging effort has concentrated primarily on the physics package, but has also established the feasibility of the overall size goal.

Testing of the complete bench unit has given very encouraging results, and the EG&G TRFS project is on schedule.

(1) EG&G, Volume I Technical Proposal, Tactical Rubidium Frequency Standard (TRFS) for the SEEK TALK Program, June 19, 1981.



Figure 1 Photograph of TRFS Mockup Unit

3.0 BLOCK DIAGRAM

A block diagram of the TRFS is shown in Figure 2. The only significant change since the original proposal is the elimination of the -5 V supply. The major sections are:

- a. The physics package which acts as a frequency discriminator to produce an error signal which indicates the magnitude and sense of the difference in frequency between the applied rf excitation and the rubidium atomic resonance.
- b. A servo amplifier which processes the error signal to produce a control voltage for a voltage controlled crystal oscillator (VCXO).
- c. A VCXO section which contains the locked crystal oscillator, circuits to produce the desired (5 or) 10 MHz output, and one divider portion of the synthesizer.
- d. A VHF section which contains the rest of the synthesizer that converts the standard output frequency into a direct submultiple of the rubidium resonance.
- e. A power section which provides supply voltages to the circuitry and has temperature controllers for the two physics package ovens.

This block diagram combines high performance, simplicity, and manufacturability. The physics package combines the best features of the integrated and discrete filter cell approaches. The synthesizer avoids the spectral asymmetries caused by mixing while using low divider factors and requiring few tuned circuits. The servo amplifier uses a low complexity cascade detector arrangement, and the power sections use efficient switching techniques.

The overall arrangement is a single frequency lock loop which contains a PLL synthesizer as a sub-loop.

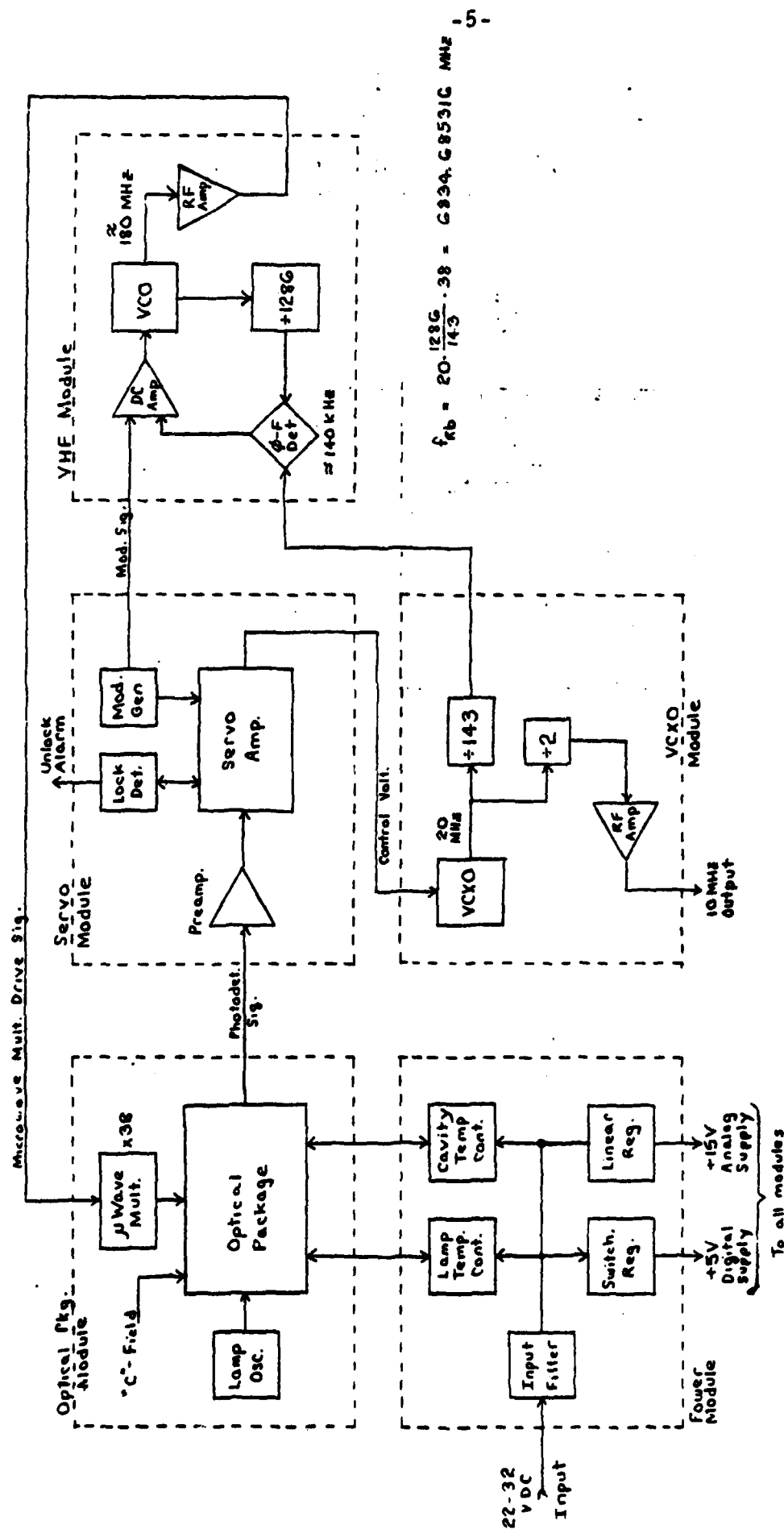


Figure 2 TRFS Block Diagram

4.0 PHYSICS PACKAGE

The heart of the TRFS unit is, of course, the physics package. EG&G began this project with the in-house development of a rubidium physics package that combines good performance with ultra-miniature size (as described in the original proposal). The features include a new concept in lamp excitation, a highly dielectrically loaded cavity, and a cell configuration that combines the best features of both integrated and discrete filtration. The basic physics package structure is shown in Figure 3.

Phase 2A of the TRFS program has refined the physics package design. The optics have been improved with a two-lens arrangement that first collimates the lamp output for better light uniformity and then efficiently collects it at the ≈ 1 cm diameter photodetector. The photodetector is a low-noise device made by EG&G and custom-packaged for this application. The C-field geometry has been improved for better ($\pm 1\%$) uniformity. A conical fiberglass piece now rigidly connects the lamp and cavity ovens for ruggedness and low vibration sensitivity.

The discriminator signal has been improved significantly by the improved optics and refined cell design.

A SRD multiplier has been incorporated into the microwave cavity, with provisions for a second coupling probe for testing. Its design is both simple and efficient, and works as a straight X38 multiplier.

Preliminary layouts have also been done to confirm that the 20 MHz VCXO and lamp exciter circuits can be repackaged inside the outer physics package shield.

The important signal parameters for the latest physics package are shown in Table I.

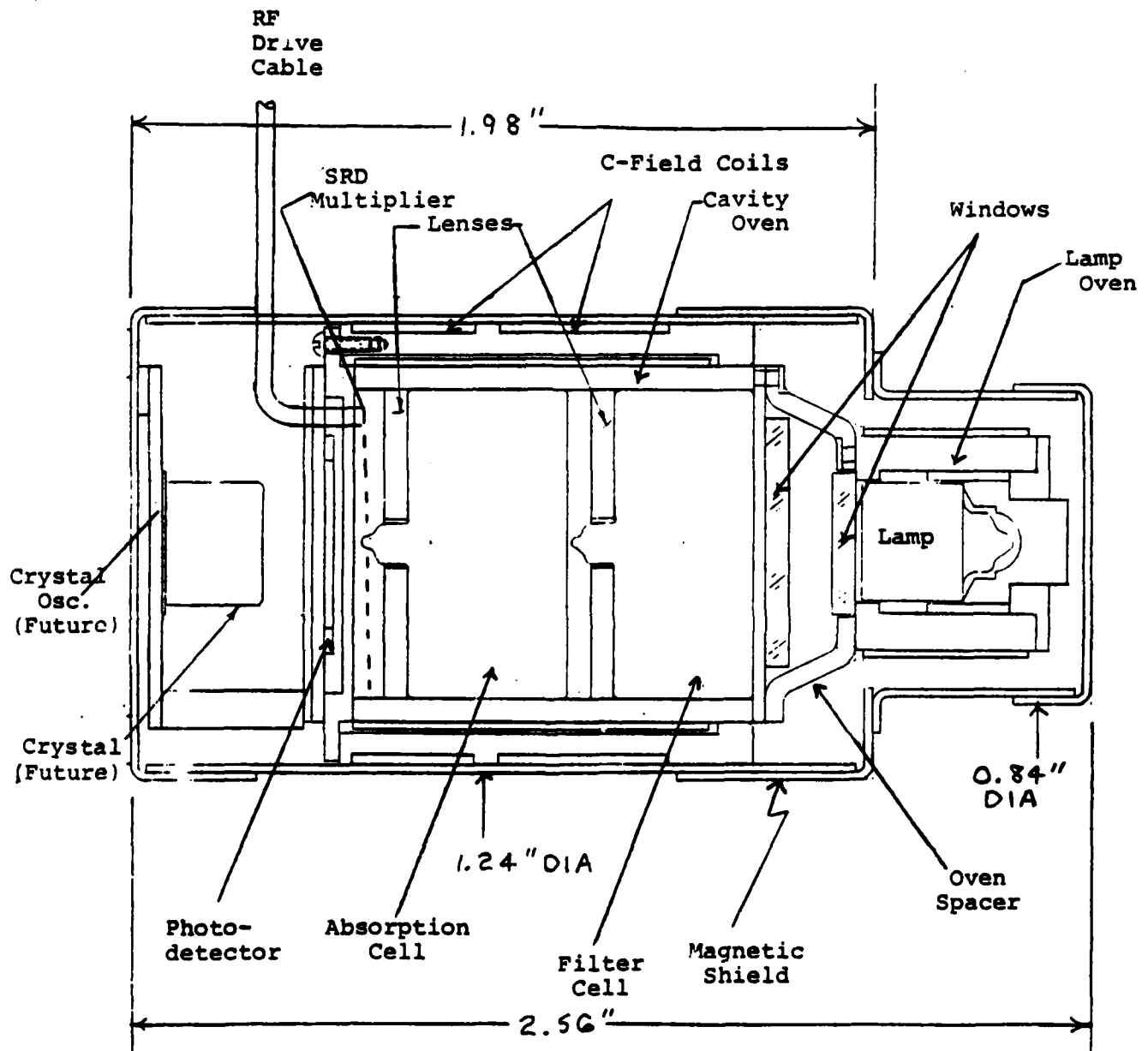


Figure 3 Layout of Miniaturized Physics Package

Table I TRFS Physics Package Signal Parameters

Parameter	Value	Units	Remarks
Lamp Oven Temperature	111	$^{\circ}\text{C}$	Chosen for $\approx$ maximum signal
Cavity Oven Temperature	73	$^{\circ}\text{C}$	Chosen for $\approx$ zero light shift
DC Photo-detector Current	125	$\mu\text{A dc}$	
Maximum Fundamental Signal at Photodetector	22	nA rms	At $f_{\text{mod}} = 235 \text{ Hz}$
Discriminator Slope at Photodetector	80	pA per 1×10^{-10}	
Lamp Oven Temperature Coefficient	-4	$\text{pp}^{10^{11}}/^{\circ}\text{C}$	Adjustable to zero by cavity temp.
Cavity Oven Temperature Coefficient	-4	$\text{pp}^{10^{10}}/^{\circ}\text{C}$	Value of $-2 \times 10^{-10}/^{\circ}\text{C}$ obtained at lower light intensity
RF Power Shift Coefficient	-7	$\text{pp}^{10^{12}}/\text{dB}$	
Linewidth	565	Hz	FW between inflection points @ full light & rf

5.0 CELL PROCESSING

The technology for lamp, filter, and absorption cell processing is available (for a low production rate). The basic performance of the lamps and cells made for the bench model is quite satisfactory. A small quantity of lamps is on hand. Several filter cells with different buffer gas fills are available for evaluation. Another absorption cell iteration is underway to make a buffer gas ratio correction for lower net temperature coefficient.

6.0 SERVO AMPLIFIER

The servo amplifier section is shown in Figure 4. It is essentially unchanged from the proposal, where the advantages of the cascade detector arrangement were described. This section has been thoroughly tested with other physics package setups and its design is now quite firm. The prototype servo amplifier board will be made smaller by the use of SIP resistor networks.

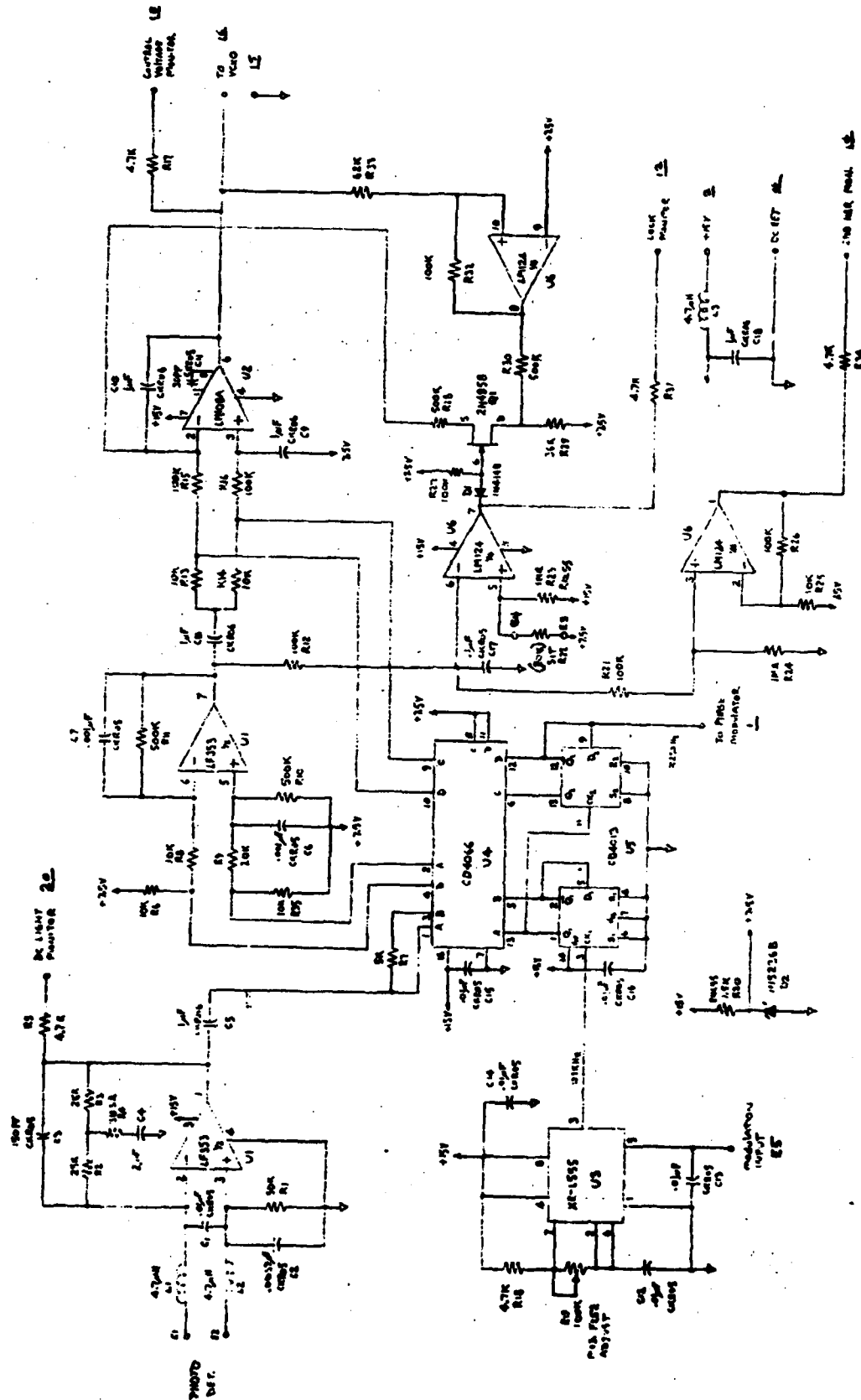


Figure 4 Servo Amplifier Schematic

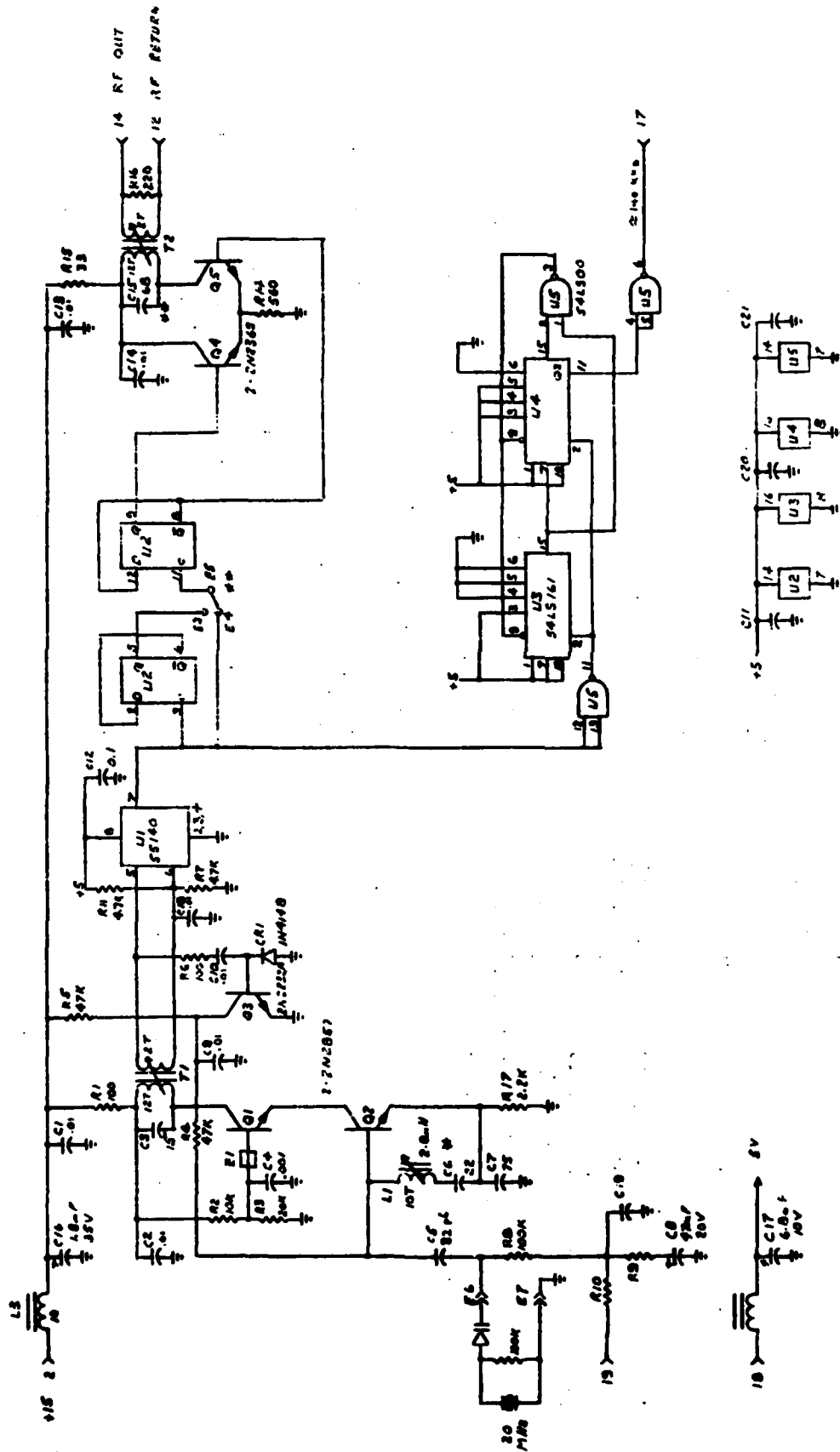
7.0 VCXO SECTION

A schematic diagram of the VCXO board is shown in Figure 5. This section is essentially unchanged from the proposal. ALC has been added to the crystal oscillator (Q3, CR1, etc.), the comparator device (U1) no longer requires a negative supply, and the output frequency can be selected as either 5 or 10 MHz.

The phase noise of the TRFS is determined primarily by this VCXO and was measured with the results shown in Figure 6. While adequate, the use of a higher Q 3rd overtone crystal is under consideration to give even lower phase noise.

The g sensitivity of this crystal is an important consideration and evaluation of this parameter is underway using a standard double balanced mixer phase noise measurement system. A worst-axis Γ value of slightly under $2 \times 10^{-9}/g$ was observed for one lot of 20 MHz fundamental SC-cut crystals in HC35/U holders. This is adequate to meet a -80 dBc spurious level under exposure to 1 g peak vibration at 100 Hz.

The VCXO crystal is mounted in a simple TO-5 component oven in the bench unit. The entire VCXO circuit (including the crystal) will be located inside the physics package (as shown in Figure 11) in the prototype version. A layout for this VCXO circuit has been done. The VCXO board will then become the Output board which will be considerably smaller, making feasible the overall prototype packaging concept. Other than these component and mechanical changes, no further redesign of this section is expected.



Notes
 C'S ARE 0.01μF VPIZ
 R'S ARE 100Ω RCH02
 * L1-C6 SERIES RESONANT @ 21MHz
 ** C16-270pF FOR 51MHz 1S74ES
 T1, T2, L1, R1C 90°C-105°C 100V 1.0μF

Figure 5 VCXO Schematic

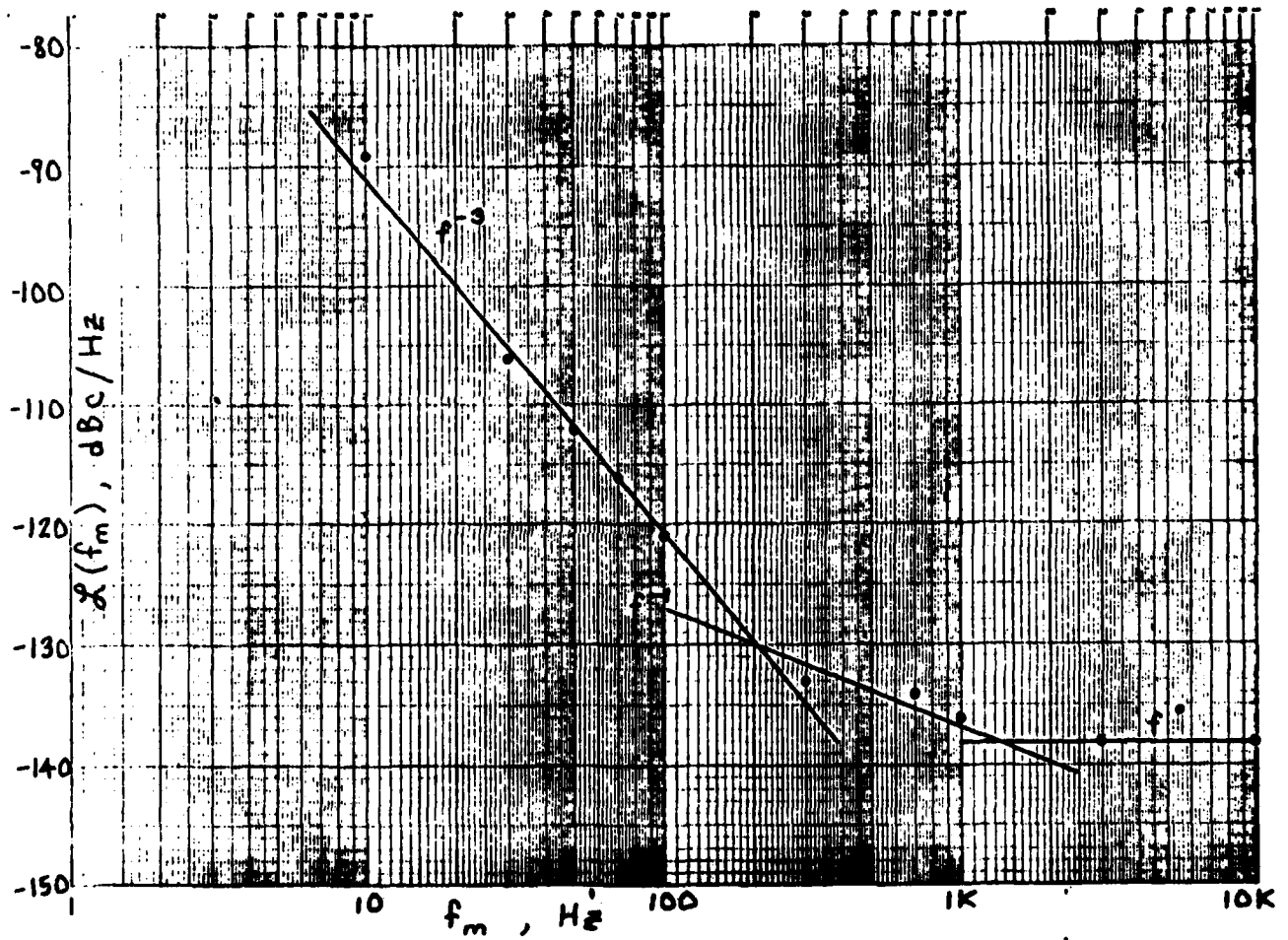


Figure 6 TRFS VCXO Phase Noise Plot (@ 10 MHz)

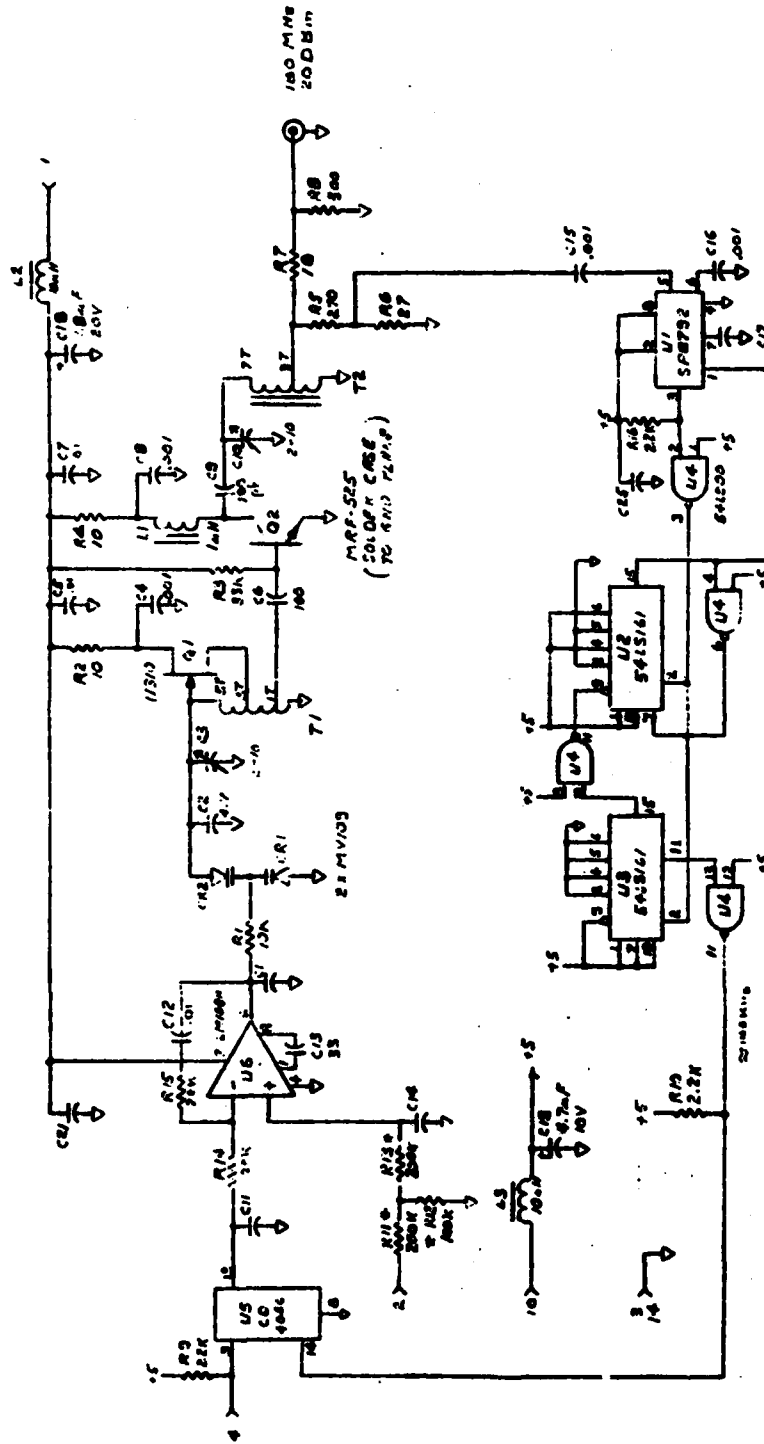
8.0 VHF SECTION

The schematic diagram of the TRFS bench model VHF section is shown in Figure 7. It is essentially the same as described in the original proposal, consisting of a ≈ 180 MHz VCO which is phase-locked to a ≈ 140 kHz reference via a $\div 1286$ divider. This signal (whose exact frequency is $20 \cdot \frac{1286}{143} = 179.8601399 + \text{MHz}$) is then amplified and multiplied by 38 to excite the rubidium resonance.

The unusual simplicity of the rf chain is based on this unique A/B synthesizer ratio that allows a high comparison frequency and thus permits a wideband lock loop. High PLL bandwidth (≥ 300 Hz) is necessary since it is a sub-loop inside the overall frequency lock loop which, for reasons of vibration immunity, wants to itself have relatively high (≥ 100 Hz) bandwidth. Even wider PLL bandwidth is desirable for ease of servo modulation.

A LC VCO was chosen for this application because its high tuning sensitivity can easily give a wide loop bandwidth. Considerable difficulty was experienced, however, with obtaining adequate spectral purity from this VCO, because the varactor is also highly sensitive to noise.

It now appears that a VCXO at ≈ 90 MHz (using a 3rd overtone crystal for low motional inductance) followed by a doubler is a better choice. A lock loop bandwidth of 300 Hz is feasible and direct FM is possible. This approach is now under investigation. The overall VHF section would then become as shown except that a ≈ 90 MHz VCXO and active doubler would be substituted for the ≈ 180 MHz LC VCO.



Notes:
 C's: 100 pF 50V
 R's: 100K 1/4W 5%
 C10: 100 pF 50V
 T10: 100 pF 50V
 T10: 100 pF 50V

Pin	Device	GND	Cap	5V
16	U2	8	220	16
16	U3	8	220	16
14	U4	7	220	14
14	U5	7	220	14

Figure 7 Schematic of Bench Model VHF Section

9.0 POWER SECTION

The power section of the bench model TRFS is shown in Figure 8. The two switching temperature controllers are essentially identical to those proposed, and this portion of the design can be considered to be quite firm. No difficulties have been experienced from switching pulse interference (≈ 100 kHz), and the TL494 devices have very little temperature rise ($\approx 8^{\circ}\text{C}$).

The power supply has changed from the proposal. A -5V supply is no longer required, and the design has been simplified to consist of a +5V series switching regulator and a +15V series linear regulator. The latter has considerable dissipation and, although reasonable for the bench model, will be reconsidered for the prototype.

NOTES:
 1. ALL RESISTORS ARE RESISTANCE INDICATED OTHERWISE
 2. ALL CAPACITORS ARE CAPACITANCE INDICATED OTHERWISE

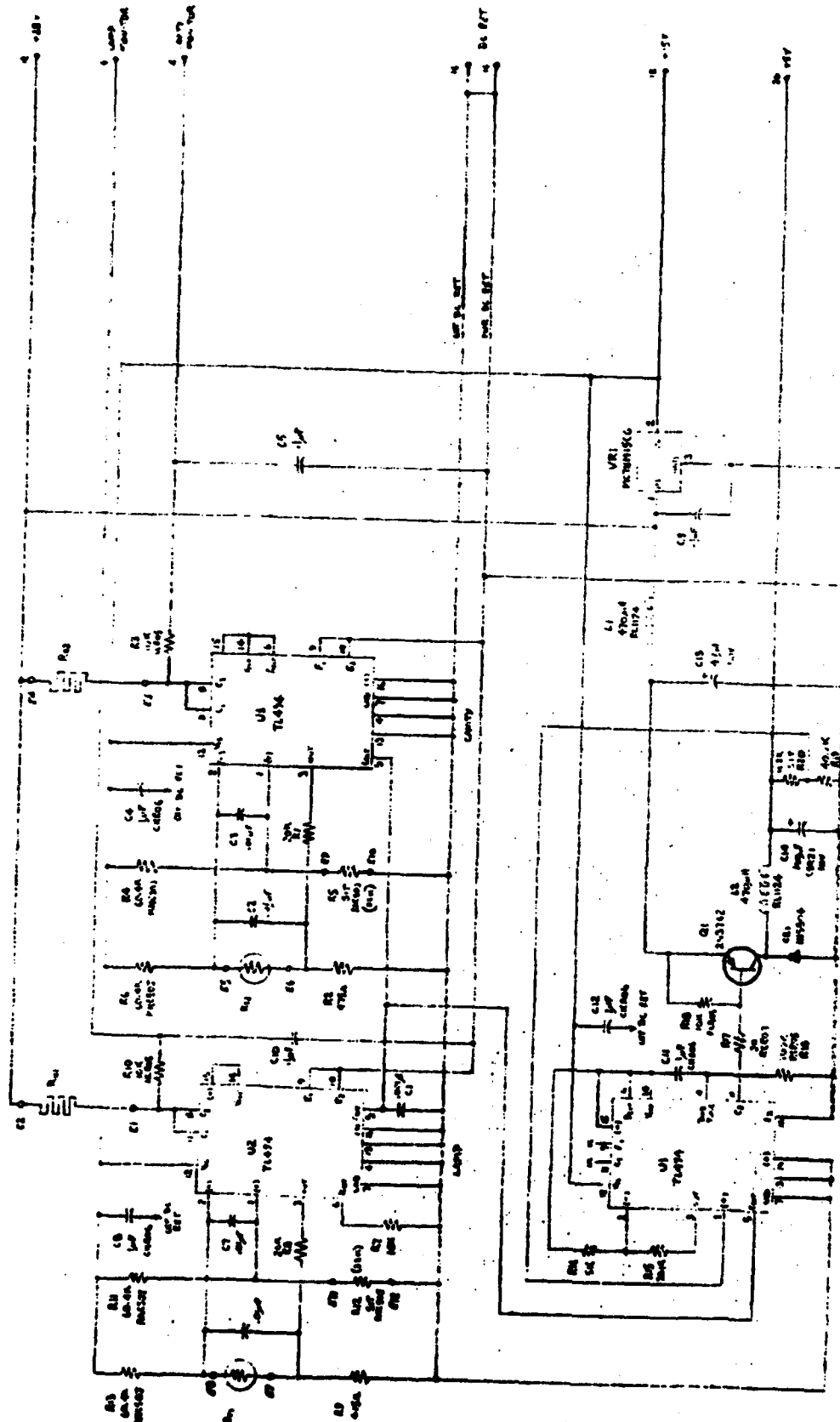


Figure 8 Schematic of Bench Model Power Section

10.0 OTHER CIRCUITS

The TRFS bench unit also contains several other small circuits that are not located on the four main circuit boards.

The lamp exciter circuit is shown in Figure 9. It operates from a separate -15 to -20 V supply for test purposes, and a packaged +15 V version will be required for the prototype. This circuit configuration has given very satisfactory performance in the bench unit tests.

The microwave multiplier circuit consists of a step recovery diode and associated matching and bias networks. In addition to the portion packaged inside the microwave cavity, a small circuit board now holds part of the matching and bias network. This will eventually be integrated onto the VHF board.

The C-field coil current is supplied by a simple series resistor in the bench unit. The prototype unit will require a stable C-field reference and adjustment network. The C-field coil coefficient is about 30 mG/mA and a current from about 1.7 to 8.3 mA is required for a tuning range of $\pm 2.5 \times 10^{-9}$. The maximum C-field sensitivity is about $\frac{\Delta f}{f} = 1 \times 10^{-8} \left(\frac{\Delta H}{H} \right)$.

1. All Resistors RCRO7 unless indicated
2. C_1 & C_3 ATC 700 Ceramic Chip
 - C_1 #700 B270 JP500X
 - C_3 #700 B221 JP200X
3. L_1 16 turns on T-25-10 Torroid
4. L_2 Delewn 1025-2B LT10K

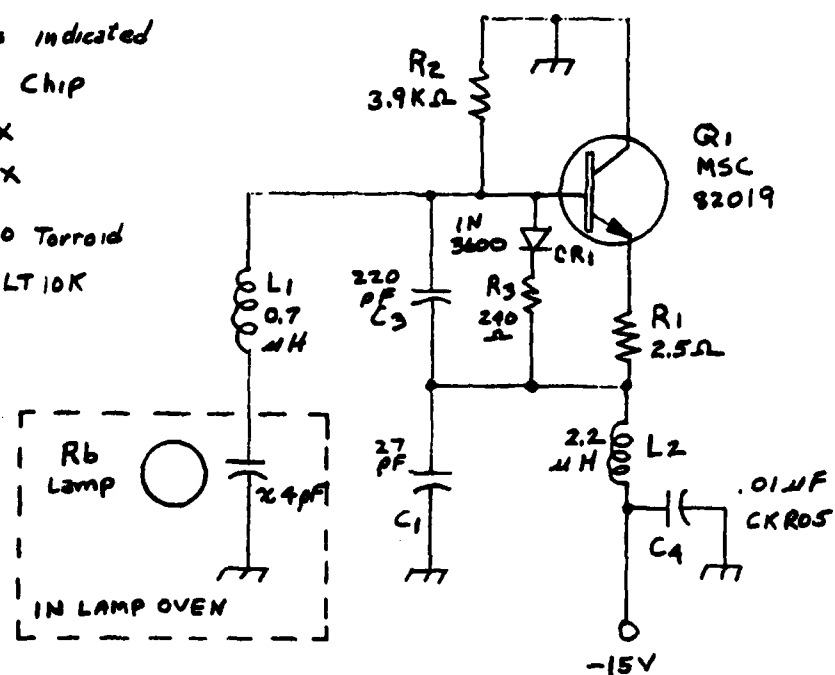


Figure 9 Schematic of Bench Model Lamp Exciter

11.0 BENCH MODEL PACKAGING

The bench model TRFS consists of the ultraminiature physics package and four circuit boards mounted flat on a 9 inch square pallet as shown in Figure 10.

The physics package is complete out to the first magnetic shield, including a custom EG&G silicon photodetector and the SRD microwave multiplier. It does not have an outer magnetic shield or internally packaged lamp exciter and VCXO circuits. The lamp exciter is housed separately in a small shield box and the VCXO circuit is on one of the main boards with the crystal in a small separate component oven.

Some testing has also involved the use of a ≈ 90 MHz VCXO with associated doubler and power amplifier and laboratory instruments such as frequency synthesizers and power supplies.

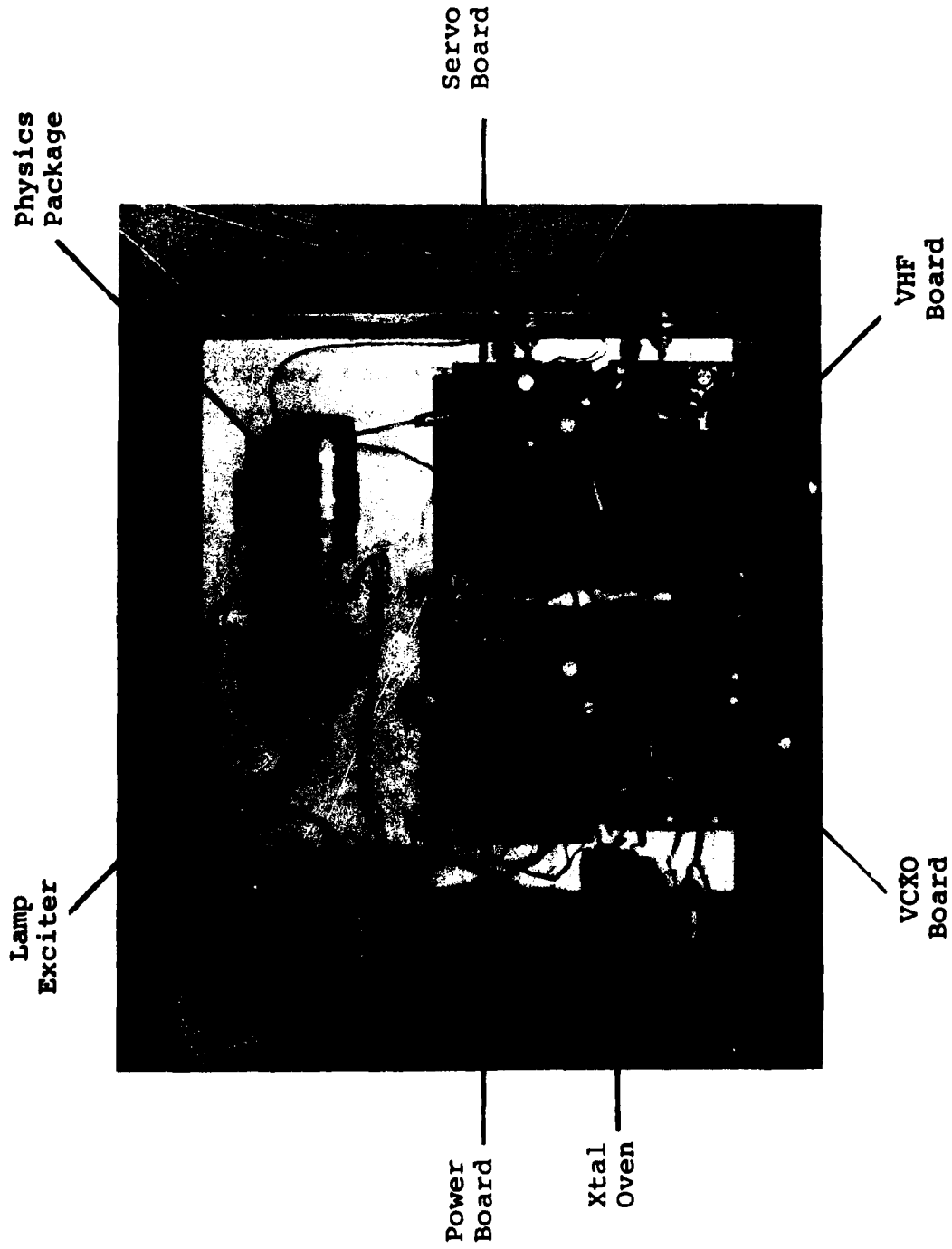


Figure 10 Photograph of TRFS Bench Model

12.0 SUMMARY OF RESULTS

Line Item 0001 of the contract requirements contains a list of specifications for the bench model TRFS unit. This report section summarizes the actual results obtained for each specification listed.

(1) Frequency. The nominal output frequency is 10 MHz (with 5 MHz as a factory option). The actual frequency is slightly low, 9.9999998 MHz or -20×10^{-9} at the center of the magnetic tuning range. This difference is easily corrected by a slightly higher ($\approx +5\%$) absorption cell fill pressure for the next iteration.

(2) Output Level. The nominal output level is 0.5 V rms into 50Ω which is 5 mW or +7.0 dBm. The actual output has been measured on the bench model and several other test boards and has ranged from + 7.1 to + 7.4 dBm, slightly higher than nominal.

(3) Harmonics. The specifications require that the output harmonics not exceed -30 dBc. The measured harmonic levels for one test board were as follows:

<u>Component</u>	<u>Level, dBc</u>
X2	-36
X3	-37
X4	-47
all others	>50 dB down

All harmonic levels are therefore adequately suppressed.

(4) Spurious Noise. The requirements specify maximum levels of phase noise at 1, 100 and 1000 Hz from the output carrier. The noise at sideband frequencies of about 100 Hz and greater is determined by the

TRFS 20 MHz VCXO. Phase noise measurements made at 10 MHz on this oscillator are shown in Figure 6. The requirements are met and, as discussed in section 7, a higher Q crystal should give even lower noise. The phase noise at sideband frequencies below about 100 Hz will be determined primarily by the signal to white-frequency noise of the rubidium discriminator signal. The measured time domain stability predicts a noise level of -74 dBc/Hz at 1 Hz from the carrier.

- (5) DC Power. This characteristic is considered a prototype design goal. The values of 13 W steady-state at 25°C and 75 W during warmup are still considered realizable.
- (6) DC Input Voltage. The power supply and oven controller circuits have been observed to perform satisfactorily over the required dc input voltage range of 22 to 32 Vdc.
- (7) Warm-Up Time. This characteristic is also considered a prototype design goal. The values are still considered reasonable goals.
- (8) Frequency Drift. Insufficient data is available to predict values for monthly and yearly frequency drift. The signal parameters of the physics package make compliance with the specified performance a reasonable expectation, particularly with regard to rf power and light shift effects.
- (9) Frequency Stability. The measured value of short-term frequency stability is 6×10^{-12} at $\tau = 10$ seconds. This yields a white-frequency noise characteristic

of about $2 \times 10^{-11} \tau^{\frac{1}{2}}$, thus meeting the requirement by a comfortable margin.

- (10) Frequency Range. A frequency trim range of 3×10^{-9} requires a magnetic bias field that varies from about 50 to 200 mG. For the measured C-field coil sensitivity of 30 mG/mA, this requirement is met with a reasonable current range of about 1.7 to 6.7 mA.
- (11) Voltage Coefficient. The largest voltage dependence is that of the C-field, which is $\frac{\Delta f}{f} = 1 \times 10^{-8} \left(\frac{\Delta V}{V}\right)$ at the worst case of maximum 250 mG magnetic bias. Assuming that the C-field current is derived by a resistor from the supply voltage V, the specified $\frac{\Delta f}{f}$ value of 1×10^{-11} for a 10% change of input voltage requires a supply stabilization of only 100:1. This is easily met by a simple IC linear voltage regulator.
- (12) Temperature Coefficient. The specifications call for an overall $\frac{\Delta f}{f}$ of under 3×10^{-10} over a range of -54 to $+71^{\circ}\text{C}$ or an average TC of less than $2.4 \times 10^{-12}/^{\circ}\text{C}$. Measurements made on the bench unit indicate that this can be realized. The largest measured oven TC is about $4 \times 10^{-10}/^{\circ}\text{C}$. This can be reduced to $1 \times 10^{-10}/^{\circ}\text{C}$ by a lower light intensity and refined absorption cell buffer gas mix ratio. An oven stabilization factor of only 100 is therefore needed, and tests have indicated that it is easily realizable. The most significant electronic factors are cavity microwave power and C-field stability. The measured rf power sensitivity is only $7 \times 10^{-12}/\text{dB}$, so

a stability of several dB over the temperature range is adequate. This is also easily realizable, particularly since the SRD multiplier itself is temperature controlled. The C-field stability is most critical at maximum magnetic bias, where a TC of about 100 ppm/ $^{\circ}$ C is tolerable. Again, this is a practical value.

(13) - (23). These items are all considered to be prototype design goals. It is particularly significant that the original size goal of 2.5 x 2.5 x 4.0 inches still seems realizable.

13.0 PLANS FOR PROTOTYPE VERSION

Phases 2B and 2C of this program call for the redesign and building of two TRFS prototypes. The following changes are anticipated as the design progresses to the packaged version of Figure 11.

- a. The 20 MHz VCXO circuit and crystal will be packaged inside the physics package.
- b. The lamp exciter circuit will be packaged inside the physics package.
- c. An outer magnetic shield will be added to the physics package.
- d. All electronic circuits will be packaged on 4 plug-in boards as follows:
 1. The VCXO board will become a smaller Output board.
 2. The VHF board will be redesigned for a VCXO.
 3. The Servo board will use SIP resistor networks, and will thereby become smaller.
 4. The Power board will include C-field circuitry and warm-up heater control.
- e. A motherboard will be added to interconnect the various boards and connectors.
- f. C-field adjustment circuitry will be added.
- g. Fast warm-up heaters will be added to the physics package oven.

The following additional features are also under consideration:

- a. Thermoelectric cooling to extend the upper ambient temperature range.

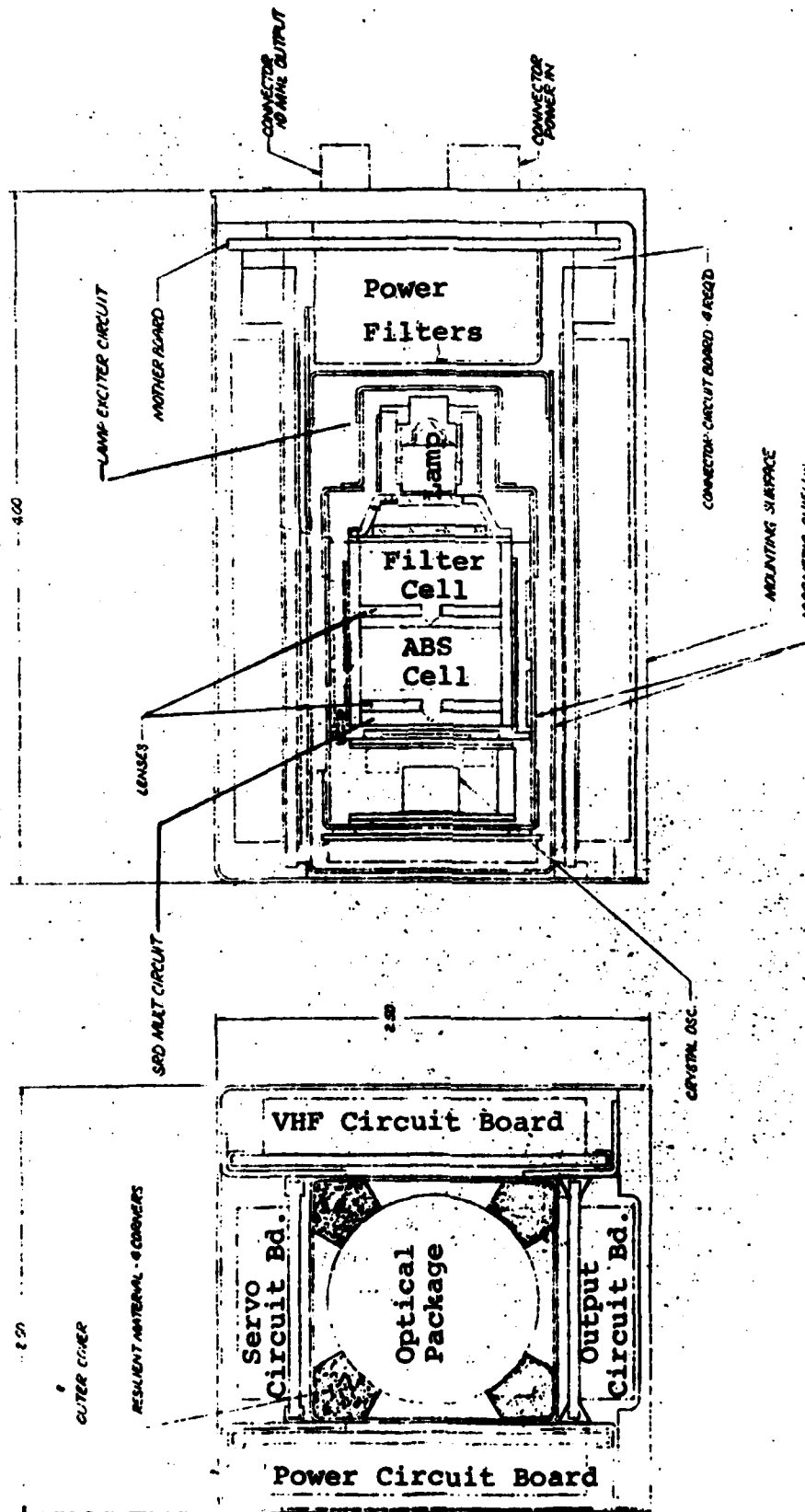


Figure 11 TRFS Prototype Packaging Layout

- b. Techniques for reduced vibration sensitivity.
- c. Circuitry for automatic syntonization to an external reference.

The TRFS design concept has now been implemented in the form of a bench version. It appears that the program can move forward without major difficulty into the prototype stage to meet the SEEK TALK requirements.



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